

# **Modeling and Analysing the Propagation of Uncertainty**

Michael B. Porter  
Science Applications International Corp.  
10260 Campus Point Drive  
San Diego, CA 92121  
phone: (858) 826-6720 fax: (858) 826-2700 email: [michael.b.porter@saic.com](mailto:michael.b.porter@saic.com)

Paul Hursky  
Science Applications International Corp.  
10260 Campus Point Drive  
San Diego, CA 92121  
phone: (858) 826-6149 fax: (858) 826-2700 email: [paul.hursky@saic.com](mailto:paul.hursky@saic.com)

Award Number: N00014-00-D-0115

## **LONG-TERM GOALS**

To develop techniques and/or models that provide error bars on relevant SONAR predictions (e.g. “range-of-the-day”). Furthermore to develop procedures for reducing the uncertainty in those resulting predictions using readily available, through-the-sensor data.

## **OBJECTIVES/BACKGROUND**

Shallow-water environments have become increasingly important for naval operations. Unfortunately, these regions are also characterized by ocean variability and, due to typically downward-refracting conditions, an increased sensitivity to bottom properties. Of course, bottom properties are also often poorly known, especially in shallow water. As a result, there is a lot of concern about 1) how to improve our knowledge of the variability and 2) providing error bars so that a predicted transmission loss can be assessed taking into account an idea of its reliability. The goal of this work is to address both these issues. Note that variability in this discussion refers to both temporal and spatial changes.

## **APPROACH**

We have followed a two-prong approach in our initial work. First, we are exploring a technique (‘adjoint modeling’) that is currently an active area of research in oceanography but is completely new to analyzing uncertainty in ocean acoustic propagation. Second, we are developing new versions of popular acoustic models that can provide rapid field calculations for ensembles of ocean environments.

The adjoint approach in oceanography addresses the problem of understanding where environmental errors in the initial conditions and forcing are causing errors in the resulting nowcasts. Thus one can run an ocean circulation model with a given initialization and wind forcing forward in time. At the end of the simulation one then performs environmental measurements, e.g., XBT’s to measure the true ocean state. Through a mathematical formalism one then derives a sort of reverse ocean circulation model (the adjoint) that can be run backwards in time to see how those errors were caused by earlier errors in the initial conditions or forcing. It turns out that there is a nice analogy between this ocean

Report Documentation Page			Form Approved OMB No. 0704-0188		
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1. REPORT DATE <b>30 SEP 2002</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2002 to 00-00-2002</b>	
4. TITLE AND SUBTITLE <b>Modeling and Analysing the Propagation of Uncertainty</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Science Applications International Corp.,10260 Campus Point Drive,,San Diego,,CA, 92121</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <b>To develop techniques and/or models that provide error bars on relevant SONAR predictions (e.g. range-of-the-day). Furthermore to develop procedures for reducing the uncertainty in those resulting predictions using readily available, through-the-sensor data.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>6</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

weather forecast problem and the one critical for an acoustic forecast, which we pursue to develop a similar way of analyzing uncertainty in the acoustic environment.

The second problem is to provide error bars along side acoustic predictions of TL or the complex acoustic field. An obvious approach is simply to do Monte Carlo simulations with an ensemble of possible environments. However, this becomes computationally expensive. The idea we have followed is to look for intermediate variables in the acoustic models that can be linearly interpolated. Thus one can run the acoustic model at the environmental endpoints, characterizing for instance the maximum and minimum possible bottom sounds speeds. All the intermediate pressure fields can then be produced through a quick interpolation.

## **WORK COMPLETED**

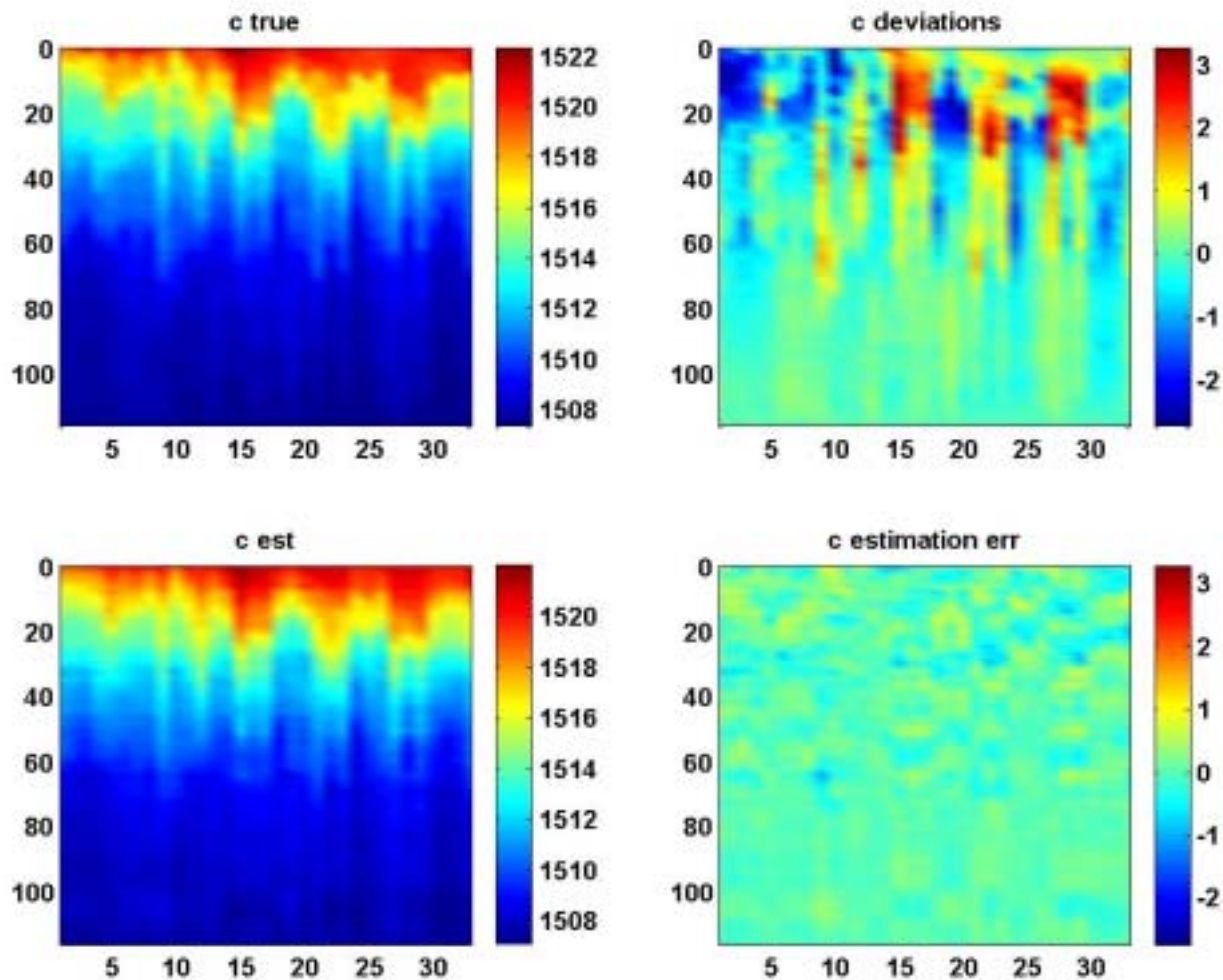
To demonstrate and develop the acoustic adjoint technique, we began with a parabolic equation model, which marches an initial acoustic field due to a SONAR, forward in range. An observation system such as a TB-23 tactical towed-array observes the acoustic field and compares the results to the ‘acoustic forecast’. We then derived an adjoint, which is sort of a backward parabolic equation, which propagates those observation errors back to the projector, providing a continuous indicator of the errors in ocean and bottom sound speed that caused those errors.

The ‘environmental endpoints’ concept was developed using the widely-used BELLHOP Gaussian Beam Model. BELLHOP provides arrival times and amplitudes for each of the echoes in the ocean channel. We wrote a Matlab post-processor that runs the model for environmental endpoints associated with bottom depth, sound speed, density, and attenuation. We then benchmarked the solution by comparing it to the solution obtained without interpolation and finally applied the fast endpoint-model to representative applications.

## **RESULTS**

Our first application of the adjoint technique considers a problem of tracking internal tides. This was really intended just as a preliminary test of the formulation; however, one may envision an acoustic barrier system that requires continuous tracking of the oceanographic variation to maintain focus on the acoustic tripwires.

Our scenario is based on the INTIMATE96 experiment. The upper left panel in Figure 1 shows the measured sound speed profile over a 35-hour period. Note the strong dips in the isotherms that are associated with the passage of internal tides. During the course of the experiment, LFM chirps were transmitted every 8 seconds. These provide our measured acoustic data (however, for our first studies, we simulate the acoustic data rather than using the measured data). We then take a mean or climatological profile and predict the observed acoustic field using this erroneous or nominal SSP. The discrepancy between measured and observed profiles was then back-propagated through the adjoint acoustic model to predict the source of those errors (that being the internal tides themselves). The lower left panel shows that the adjoint model provides an excellent tracking of the internal tides.



**Figure 1.** *Results of inversions for internal tides using our adjoint model. The top panels show the true sound speed structure over time (in both raw form and measured as deviations with respect to the mean); the bottom panels show the results estimated by the adjoint model.*

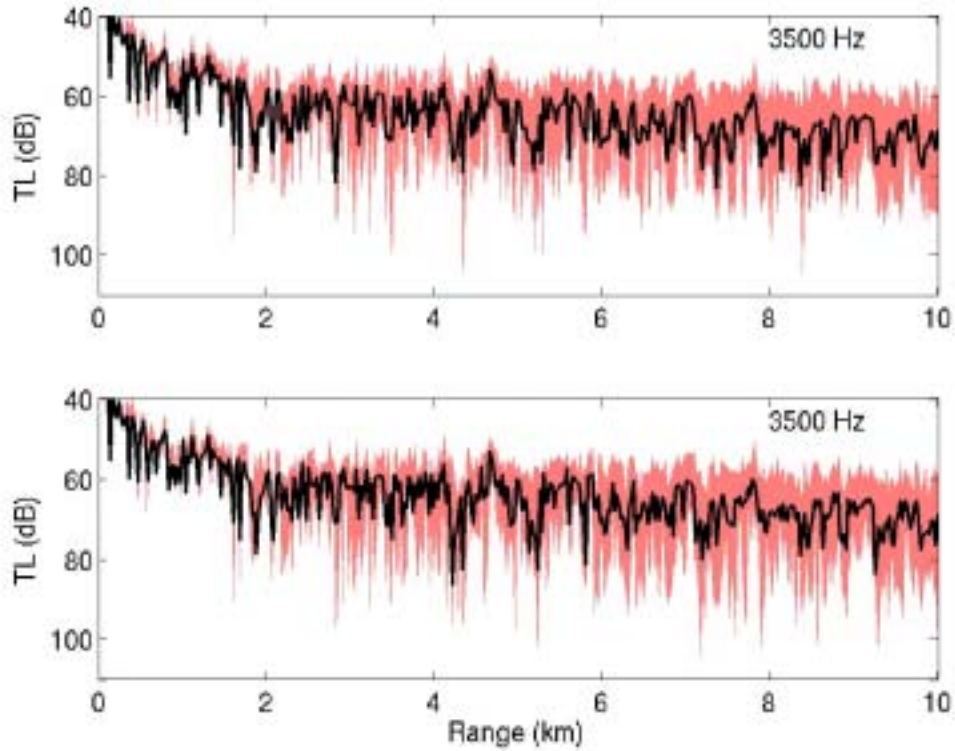
Of the many factors that can contribute to TL prediction, the seabed properties often have the greatest impact and are probably the least well known. Using Monte-Carlo methods, error bars can be estimated by calculating TL over thousands of realizations of the seabed. With adequate sampling of the possible environmental values the bounds on TL (error bars) can be determined. The difficulty with Monte-Carlo methods is the computational load is usually very high.

In collaboration with M. Siderius, we have developed a Gaussian beam interpolation technique for computing TL that can be used with Monte-Carlo methods since run times are reduced by factors of 100-1000. Ray/beam-based propagation models are common in the SONAR community but usually a new trace is required each time environmental conditions change. Even though ray methods are computationally fast, if thousands of calculations are needed the costs become significant. Here, beam-trace calculations are made only for the extreme values for each of the environmental parameters (e.g. 6 ray calculations for 3 seabed parameters). The well-behaved ray arrival amplitudes and delays are then interpolated for each random set of parameters drawn in the Monte-Carlo simulation. The TL, at

each frequency  $\omega$ , is then calculated by summing over all arrival amplitudes ( $A_n$ ) and delays ( $t_n$ )

according to,  $TL(\omega) = -20 \log \left| \sum_{n=1}^{N_{arr}} A_n \exp(i\omega(t - t_n)) \right|$ . In Fig. 1, the TL is shown at 500 and 3500 Hz for

100 random sets of seabed parameters generated by the interpolation method and by a 100 ray trace calculations. The TL is shown for a single environmental realization (black line) and for all realizations (red filled area). The estimates for TL and the TL variability are nearly the same (except in some of the nulls where there is little acoustic energy) for both calculations. However, the interpolation method produces the figure approximately 100 times faster.



**Figure 1: (a) Top panel shows TL calculation using ray interpolation and lower panel shows computed ray trace TL at 3500 Hz for 100 random environments (100 m water depth, seabed sound speed can take values from 1550-1650 m/s, attenuation from 0-1 dB/wavelength and density from 1-2.5 g/cm<sup>3</sup>). Black lines show TL for a single environmental realization and red filled area shows the extreme values over the 100 environmental realizations. The interpolated ray method provides essentially the same results as the direct Monte Carlo method, but runs about 100 times faster.**

## IMPACT/APPLICATIONS

The importance of this process is described under “Background/Objectives”: this work is producing valuable techniques for both analyzing the causes scientifically and predicting the effects of

uncertainty for the SONAR operator. In parallel, we have also been applying these techniques for a system designed to predict the performance of navy SONAR on marine mammals.

## RELATED PROJECTS

This work is being performed in association with researchers at Scripps Institution of Oceanography, Duke University, and Orincon, whose annual reports are part of this volume. As mentioned above, related work is also being performed in connection with the Effects of Sound on the Marine Environment program, which also has a need for associating error bars with threshold levels for mammal exposure to sound.

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